

## **Using NOGAPS Singular Vectors to Diagnose Large-scale Influences on Tropical Cyclogenesis**

PI: Prof. Sharanya J. Majumdar  
RSMAS/MPO, University of Miami  
4600 Rickenbacker Causeway  
Miami, FL 33149

Phone: (305) 421 4779 Fax: (305) 421 4696 Email: [smajumdar@rsmas.miami.edu](mailto:smajumdar@rsmas.miami.edu)

Co-PI: Dr Melinda S. Peng, Dr Carolyn A. Reynolds, Dr. James D. Doyle  
Naval Research Laboratory  
7 Grace Hopper Avenue  
Monterey, CA 93943

Peng: Phone: (831) 656 4704. Email: [melinda.peng@nrlmry.navy.mil](mailto:melinda.peng@nrlmry.navy.mil)  
Reynolds: Phone: (831) 656 4728. Email: [carolyn.reynolds@nrlmry.navy.mil](mailto:carolyn.reynolds@nrlmry.navy.mil)  
Doyle: Phone: (831) 656 4716. Email: [james.doyle@nrlmry.navy.mil](mailto:james.doyle@nrlmry.navy.mil)

Co-PI: Prof. Chun-Chieh Wu  
Dept of Atmospheric Sciences, National Taiwan University, No. 1, Sec. 4, Roosevelt Rd, Taipei  
10673, Taiwan  
Phone: +886-2-2363-2303. Email: [cwwu@typhoon.as.ntu.edu.tw](mailto:cwu@typhoon.as.ntu.edu.tw)

Co-PI: Prof. David S. Nolan  
RSMAS/MPO, University of Miami  
4600 Rickenbacker Causeway  
Miami, FL 33149  
Phone: (305) 421 4930 Fax: (305) 421 4696 Email: [dnolan@rsmas.miami.edu](mailto:dnolan@rsmas.miami.edu)

Grant Number: N000140810250  
<http://www.rsmas.miami.edu/personal/myamaguchi/>

### **LONG-TERM GOALS**

The overarching goal is to improve our understanding of synoptic-scale influences on tropical cyclone (TC) formation and motion in the western North Pacific Ocean, in the context of error growth in forecast models. Benefits to the Navy would include improved forecast skill of the structure and track of developing and recurring TCs.

### **OBJECTIVES**

The first objective is to connect Singular Vector (SV) and ensemble perturbation growth to synoptic-scale dynamical influences on tropical cyclone formation and structure change. The second objective is to extend these investigations towards vortex initialization and analysis of tropical cyclone structure

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in high-resolution models. The goal is to extend these methodologies into the Navy's COAMPS-TC framework.

## APPROACH

Several sensitivity and predictability studies have been completed. The approach has been to investigate perturbation growth in SVs and in ensemble predictions, for cases from ONR's Tropical Cyclone Structure (TCS-08) field experiment.

The sensitivity patterns, evolving horizontal and vertical structure and error growth associated with SVs have been investigated. The connection between perturbation structures and synoptic-scale processes influencing TCs has been explored. Hypotheses for SV growth have been formulated and published by Munehiko Yamaguchi, the graduate student funded on this grant, using a barotropic model with idealized vortices and initial conditions from the TCS-08 case of Typhoon Sinlaku. A highly configurable vortex initialization method based on theory and observations has been designed to rapidly provide initial estimates of TC structure in high-resolution models, for TC initialization and predictability studies. A manuscript on this method and the sensitivity of numerical simulations to the prescribed initial vortex has been submitted to *Monthly Weather Review*. In 2012, the software is being converted from MATLAB to FORTRAN for transition and use by Navy researchers and collaborators.

## WORK COMPLETED

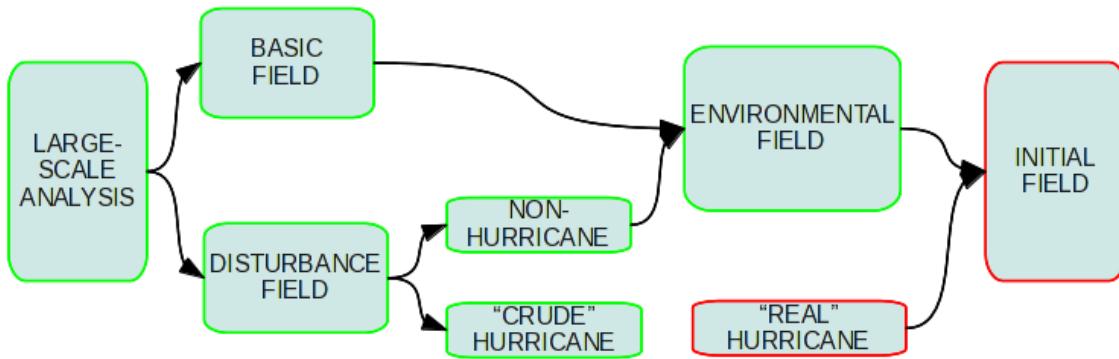
The research on Singular Vectors has been described in the 2011 Annual Report, and is now published in *J. Atmos. Sci.* (Yamaguchi et al. 2011). We expect that the results produced from this study will be important in identifying processes associated with error growth in more sophisticated models such as COAMPS-TC, and this will be investigated in the upcoming year. Yamaguchi received his Ph.D. in 2011.

The configurable framework for vortex initialization has been developed in MATLAB, and has partially been converted to FORTRAN. The motivation is to offer software for use by the community for a variety of predictability and sensitivity studies, and to provide a benchmark upon which high-resolution data assimilation schemes must improve upon. Software to remove the vortex, similar to the operational version at the Geophysical Fluid Dynamics Laboratory (GFDL, Kurihara et al. 1995), has been completed in both MATLAB and FORTRAN, together with different configurations of the radial and vertical structure of the vortex comprising a primary and secondary circulation. A manuscript has been submitted and is under review in *Monthly Weather Review* (Rappin et al. 2012). The results reported below focus on this part of the research.

## RESULTS

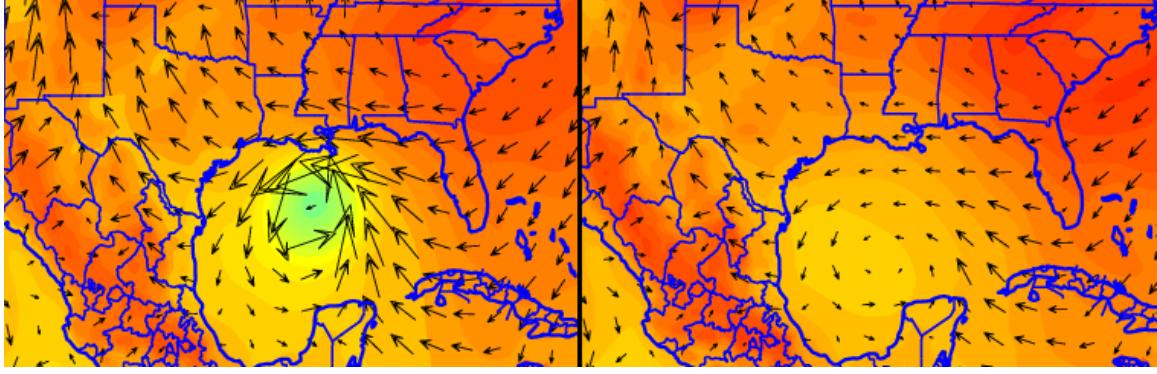
The vortex initialization framework allows for a variety of specifications of flow in the boundary layer and free atmosphere, with users being able to seamlessly introduce their own configurations. In this study, radial profiles based on a modified Rankine vortex and on a profile fit to historical observations (Willoughby et al. 2006) have been introduced for the primary circulation. These profiles can be constructed based on any observations of the maximum azimuthal wind and its radius. For the secondary circulation, a realistic three-dimensional boundary layer structure has been introduced,

based on a nonlinear similarity model designed by an ONR-funded PI Ralph Foster (University of Washington) (Foster 2009). Configurable parameters include the boundary layer height and eddy diffusivity. In the free troposphere, the vertical structure of the axisymmetric tangential wind is based on a thermal wind balanced, moist neutral steady state model (Emanuel 1986). Conservation of angular momentum in the boundary layer is exploited to match the flow between the boundary layer and the free troposphere. A flow chart showing the components of the framework is illustrated in Fig. 1. The elements in green have been completed in both MATLAB and FORTRAN. The elements in red are nearing completion in FORTRAN and will be transferred to the Navy when finished.



**FIGURE 1.** Flow diagram of vortex configuration framework. Elements in green have been completed both in MATLAB and FORTRAN. Elements in red are being translated from MATLAB to FORTRAN and will be completed shortly.

Global models such as NOGAPS and the NCEP Global Forecast system include an unrealistically coarse TC vortex in its large-scale analysis, as is exemplified in Fig. 2a. The removal of this vortex results in a smooth basic field, illustrated in Fig. 2b. The configurable, more realistic TC vortex can then be added to this basic flow, while ensuring dynamic and thermodynamic balance. It is worth noting that the speed of the vortex removal step, which takes the majority of the time in the initialization, is 100 times faster after the conversion of the software from MATLAB to FORTRAN.

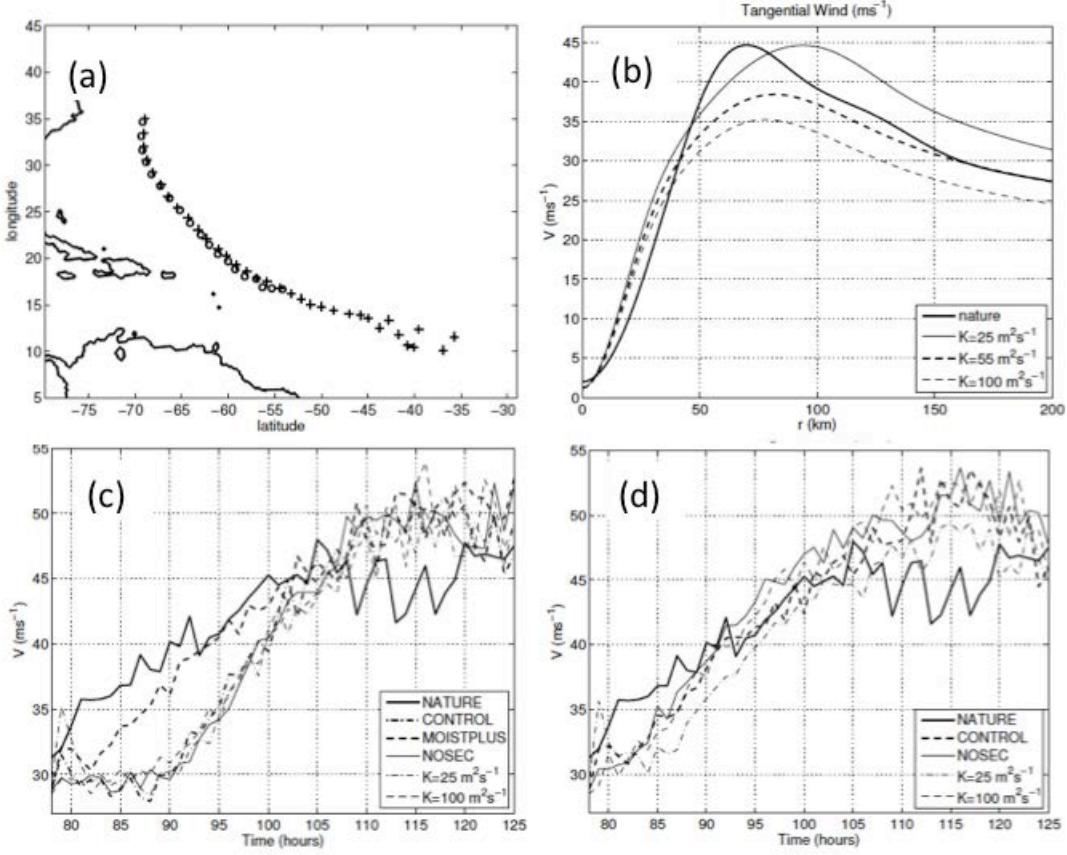


**FIGURE 2.** Perturbation hydrostatic pressure (shaded) and wind vectors at the top of the planetary boundary layer, for a tropical cyclone in the Gulf of Mexico. (a) NCEP Global Forecast System analysis field, interpolated onto WRF grid. (b) Basic flow field, with vortex removed.

Observation system simulation experiments have been completed using the Weather Research and Forecasting (WRF) model and the MATLAB version of the vortex initialization code. ‘Nature runs’ were developed for a realistic long-lived tropical cyclone. Numerical simulations with the newly configured vortex replacing the ‘nature’ vortex were then conducted for a variety of vortex configurations to test the sensitivity of the methodology to the key tunable parameters, and to identify how forecasts are compromised by the introduction of this synthetic (but high-resolution) vortex. These numerical experiments were performed at three distinct stages of the TC life cycle: prior to intensification into a hurricane-strength vortex; during the intensification phase; and the steady-state phase after intensification. The only variations were structural, given an identical environmental flow and track (Fig. 3a). Parameters such as eddy diffusivity (Fig. 3b) were varied. The main findings, reported in Rappin et al. (2012), are as follows:

- a. There is an inevitable spin-down of the vortex in the first 12h after initialization, as the vortex adjusts dynamically and physically to the model (Fig. 3c).
- b. Given this adjustment, any sensitivity in the intensity evolution to boundary layer eddy diffusivity or initial divergent flow is not apparent (Fig. 3c).
- c. An artificial moistening of the vortex eyewall by 15% dramatically reduces this spin-down, and yields accurate 3-day forecasts of the maximum azimuthally averaged tangential wind (evaluated versus the nature run). This is due to the ability to maintain sustained deep convection in the moistened vortex. (Fig. 3d)
- d. For the moistened vortex, very little sensitivity was found to (i) the boundary layer eddy diffusivity or (ii) the secondary circulation. (Fig. 3d)

These findings were consistent through all phases of the tropical cyclone’s evolution.



**FIGURE 3.** (a) Track of ‘nature’ run (+) and ‘control’ simulation which uses an eddy diffusivity of  $K=55 \text{ m}^2 \text{s}^{-1}$ . (b) Radial profiles of tangential wind for different values of eddy diffusivity. (c) Two-day forecasts of maximum azimuthally averaged tangential wind  $V$ , for the nature run (thick black line) and several WRF simulations initialized with different configurations including the control, different eddy diffusivity ( $K=25$ ,  $K=100$ ), enhanced moisture (MOISTPLUS), and with no secondary circulation (NOSEC). (d) As in (c), but with 15% moisture enhancement in all configurations. Forecasts were initialized at +72h.

In the final year of the project (2013), the FORTRAN code will be completed, and different prescriptions of the secondary circulation, and in particular the boundary layer, will be examined for use. Investigations into why the sensitivity was minor in the initial experiments will be conducted. Additional sensitivity experiments to specification of tropical cyclone size and vertical structure will be considered.

## IMPACT/APPLICATIONS

The scientific impact will be an improved understanding of the underlying environmental and internal mechanisms that influence tropical cyclone evolution. This understanding will be coupled with a quantitative knowledge of error growth in global models. High-resolution simulations, vortex initialization and examination of perturbation growth will be performed in collaboration with the COAMPS-TC team at NRL Monterey, leading to improved Navy forecasts of TC structure.

## TRANSITIONS

A preliminary version of the vortex configuration software has been used by Dr William Lewis at the University of Wisconsin, for his own vortex initialization and assimilation studies as part of a NOPP project (PI: C. Velden, CIMSS/University of Wisconsin). Brian McNoldy (Senior Research Associate II at the University of Miami) has been carrying out the code translation (from MATLAB to FORTRAN) and will make extended visits to NRL Monterey in 2013 to transfer the code onto Navy computers and to present the methodology and results.

## RELATED PROJECTS

This project is related to that funded by the TCS-08 grant N000140810251: “Advanced Satellite-Derived Wind Observations, Assimilation, and Targeting Strategies during TCS-08 for Developing Improved Operational Analysis and Prediction of Western North Pacific Tropical Cyclones”, on which Majumdar is a Co-PI. The NOGAPS Singular Vectors are also being investigated in this grant (see 2012 report from this grant, PI Velden). The high-resolution vortex initialization tools developed as part of this project are being used in the collaborative NOPP grant between the PI and CIMSS Wisconsin, NRL Monterey and NCAR, on assimilating satellite data to improve forecasts of TC intensity change.

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## **HONORS/AWARDS/PRIZES**

PI Majumdar was appointed a Co-Chair of the American Meteorological Society's annual conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans and Land Surface (IOAS-AOLS), held at the AMS Annual Meeting.